A SYSTEM FRAMEWORK OF THE COST AND ENERGY RELATIONSHIP OF ZERO CARBON BUILDINGS FROM THE LIFE CYCLE PERSPECTIVE

Jie Wang[1] and Wei Pan

Department of Civil Engineering, The University of Hong Kong, Hong Kong

Zero carbon building (ZCB) has emerged as an innovative approach to addressing the shortage of energy supply and carbon emissions from the building sector. The majority of ZCBs worldwide are mainly driven by government policy, some with financial incentives. In such cases, the social and environmental benefits of ZCBs are prioritised over their economic efficiency. Previous studies of ZCB were largely technical solutions oriented; some examined the impacts of zero carbon design solutions on the building's economic efficiency. However, there is a lack of exploration of the cost and energy relationship of ZCBs. The aim of this paper is thus to develop a system framework of such relationship of ZCBs from the life cycle perspective. The research was carried out through a critical literature review. The life cycle approach was adopted to examine the scopes of costs and energy consumption of ZCBs. A system framework is then developed to indicate how to define the scopes of costs and energy consumption of ZCBs and elaborate how to further proceed to the examination of their relationships. The system framework embraces two layers, i.e. internal and external layers. The internal layer illustrates the interior relationships between the cost, energy and lifespan of ZCBs through a three-dimensional conceptual model; the external layer describes outside context including stakeholder, climatic context and regulatory context. The results of the review suggest that there is a significant extent of inconsistency in defining the scopes of both costs and energy consumption of ZCBs. That is attributed to the confusion and dimness in the definition of both buildings' costs and energy consumption. Such inconsistency hinders the cost-energy relationship from being revealed. The findings should inform the building design decisions about the trade-offs between buildings' economic efficiency and carbon emissions.

Keywords: energy consumption, life cycle cost, zero carbon building.

INTRODUCTION

Buildings take up nearly 45% of the worldwide energy consumption and carbon emissions (Butler, 2008). ZCBs are therefore emerged as an effective approach to alleviating energy demand and carbon emissions from the building sector (Moore, 2012). Despite its prominent environmental benefits, the uptake of ZCBs is presently slow from the global practice. The majority of ZCBs worldwide are mainly driven by government policy, some with financial incentives. In such cases, the social and environmental benefits of ZCBs are prioritised over their economic efficiency.

There is an increasing awareness of the need for adopting life cycle cost (LCC) approach into the trade-offs between buildings' economic efficiency and energy

[1] jwang14@hku.hk

Wang, J and Pan W (2015) A system framework of the cost and energy relationship of zero carbon buildings from the life cycle perspective *In:* Raidén, A B and Aboagye-Nimo, E (Eds) *Procs 31st Annual ARCOM Conference*, 7-9 September 2015, Lincoln, UK, Association of Researchers in Construction Management, 297-306.

consumption. Buildings are durable and building decisions have long-term consequences (Ryghaug and Sørensen, 2009). Sesana and Salvalai (2013) pointed out as high as 80% of the operational costs of standard new buildings can be saved through integrated energy system designs. Yet often, the mere concern for the investors is the initial capital investment when they make decisions about, e.g. building design, equipment, energy systems (Jakob, 2006; Sesana and Salvalai, 2013). With this praxis, the short-term decision-making fully neglects the ongoing operation energy consumption and associated incurring costs, which may result in a not cost-effective solution.

Important early adoptions of LCC approach have taken place in recent research area of the economic effectiveness and energy performance of ZCBs. However, there is a significant extent of inconsistency in defining the scopes of the cost and energy consumption of ZCBs in the current research, since they are not explicitly formulated in the available guidelines and standards. That is attributed to the confusion and dimness in the definition of both buildings' costs and energy consumption. Such inconsistency hinders the cost-energy relationship from being revealed. Few researches have studied how to explore the cost and energy relationship of ZCBs. Gustavsson *et al*(2010) penetratingly pointed out that connections, trade-offs and synergies between the costs and energy consumption of a building in different phases of the life cycle must be identified, allowing an optimisation of building construction and operation practices to reduce environmental impacts in a cost effective way. Therefore, the purpose of this work is to develop a system framework of such relationship of ZCBs from the life cycle perspective. To achieve this, a literature review was conducted on the existing research. The understanding from this review paves way for the development of the system framework to be proposed.

CRITICAL REVIEW OF COSTS AND ENERGY CONSUMPTION OF ZCBS

A series of terms sharing similar meanings with ZCBs, e.g. zero carbon, nearly zero energy or net-zero energy building are all commonly found in the corresponding literature. These terms initially stem from the building energy policies of a number of different regions or countries, i.e. the United Kingdom, the European Union and United States (DCLG, 2006; Treasury HM, 2011; Crawley *et al*, 2009; EU. Directive, 2010) and are thereafter widely adopted within the research and industry. Notwithstanding, it is recognized that the grounded assumptions and realizing methodologies for the concepts of ‘zero carbon building’ and ‘zero energy building’ (ZEB) are different (Pan and Ning, 2014). The term ‘zero carbon building’ (ZCB) is sometimes interchangeably congruent with ‘zero energy building’ (ZEB) or many related terms (Pan, 2014). Hence, the term ‘zero carbon building’ (ZCB) is used collectively in this paper. Analysis presented in this research builds upon the previous application of life cycle approach on costs and energy performance analysis of ZCBs. An examination of the previous research was carried out to explore the scopes of costs and energy consumption of ZCBs (Figure 1).

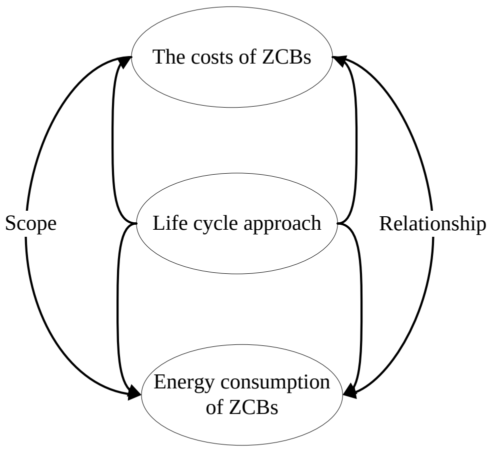

Figure 1: The review framework

The industry to date has recorded a limited number of ZCBs case with verifiable cost and energy performance data (Hootma, 2012).Owing to the insufficient data available to the public of the status quo, there have been scant research on life cycle cost and energy consumption of ZCBs. In some recent research, this research topic starts to be addressed from the lens of case study. After reviewing the existing research, the key technical elements for these studies were thereby identified, i.e. lifecycle stage, building type, cost scope, energy scope and lifespan. The representative researches were selected in order to cover as many different aspects for these five technical elements as possible for comparison and to increase information accessibility. The five technical elements for the enumerated papers were then profiled in the table 1.

Table 1: A review of the life cycle cost and energy consumption of ZCBs

Author	Lifecycle stage	Building type	Cost scope	Energy scope	Lifespan
Zhu *et al*. (2009)	Installation, operation	residential house	capital investment, cost saving from actual energy consumption(electricity, natural gas, and water)	Operation energy (electricity: actual use)	each technology lifespan
Marszal and Heiselberg (2011)	Installation, operation, maintenance, replacement demolition	residential house	Direct costs for electricity, water and potential penalty	Operation energy (heating, cooling, domestic hot water, ventilation)	each technology lifespan

Table 1(Continued): A review of the life cycle cost and energy consumption of ZCBs

Author	Lifecycle stage	Building type	Cost scope	Energy scope	Lifespan
Kneifel (2010)	Installation, operation, maintenance, end of study period	commercial building	all direct costs for end-user's actual electricity consumption	Operation energy (electricity: actual use)	1,10,25,40 years
Moore (2014)	Installation, operation, maintenance, resale value	residential house	capital investment, costs for electricity and gas consumption	Operation energy(electricity: actual use)	60 years

Lifespan of the building

It is acknowledged that the lifespan applied in LCC research of ZCBs can significantly influence the economic outcomes (Aktas& Bilec, 2012; Mequignon, *et al*. 2013). However, there is no universal standard for what the lifespan of a building should be (Moore and Morrissey, 2014), and yet, longer lifespans are more effective to capture all relevant costs of owning and operating a building (Kneifel, 2010). Different assumed lifespans, like 50 years or 60 years, have been applied within LCC research of ZCBs (Moore& Morrissey, 2014; Morrissey& Horne,2011). Moreover, lifespans are also set based on the study periods (Kneifel, 2010). Last but not least, the functioning times for each individual technology component are occasionally referred to help set the lifespan (Zhu *et al*. 2009; Marszal and Heiselberg, 2011). The variety elucidated above demonstrates an absence of consensus on how to set the lifespan within LCC research of ZCBs.

Lifecycle stage of building

The lifecycle stage division is closely related to the scopes of costs and energy consumption of ZCBs. However, the stages divided in the existing literatures appear to be widely inconsistent, which will consequently affect the consistency of the scopes of costs and energy consumption. As described in table 1, Zhu (2009) only considered the installation and operation stages. While, Aye *et al*. (2000) divided the building lifecycle into three stages, i.e. construction, operation and disposal stages. Furthermore, Cuéllar-Franca and Azapagic (2014) even took the material manufacture stage into the building's lifecycle account, which extends the building's lifecycle upward to the pre-construction phrase. Even though the international standard ISO 15686-5(BS 2012) has already given a proposition in terms of building lifecycle in which the full building lifecycle covers construction, operation, maintenance and end-of-life stages, the lifecycle stages divided in the existing research still vary from case to case.

Cost scope

The cost scope is set to cover the total cost of a building over its lifecycle including upfront capital costs, operation costs, maintenance costs and the building's residual costs at its end of life. The most inconsistency concerning the definition of the cost scope mainly lies to the operation costs. Since LCC covers all the costs arose throughout the building's lifespan, the various expenditures associated with running of the building, e.g. the costs for energy consumption, water usage and nature gas, etc., certainly should be included. However, not all the energy costs are fully covered in the existing research. Kneifel (2010) solely concerned the costs for the end-user's total electricity consumption. Moore (2014) further covered the costs for both the electricity and gas consumption.

Energy scope

Theoretically, when concerning the energy consumption of a building throughout its lifespan, three phrases, i.e. before-use, use and after-use, will be included into the building's lifecycle, covering the nine key stages of raw materials extraction, transportation to factory, manufacturing, transportation to site, construction and installation, operation, maintenance and refurbishment, deconstruction and recycling or landfill(Pan, 2014). All these phases have to be considered in order to minimize the life cycle primary energy use and carbon emission of a building (Gustavsson *et al*., 2010). A reflection of the previous life cycle energy research of ZCBs is that most of them have considered only the final energy use in the operation stage. However, few study has focused on the energy consumption implications of before-use and after-use of ZCBs. Typical buildings constructed today use most of the life cycle energy consumption during the operation phase (Winther and Hestnes, 1999; Scheuer, 2003; Adalberth, 2000; Feist, 1997). It seems that operation energy becomes relatively more important to decrease the building's lifecycle energy use, which may result to the sacrifice of the energy consumed in construction or final demolition stages.

Moreover, another reflection is the energy consumption associated with the occupant behaviours. The historical definitions of ZCB or ZEB are mainly based on annual energy use for the building's operation (heating, cooling, ventilation, lighting, etc.) that covers the occupants' entire actual energy consumption (Sesana and Salvalai, 2013; Entrop *et al*., 2010). Nevertheless, the energy scope is gradually narrowing down with an increasing awareness of the impacts that occupant behaviours have on the energy consumption. Hence, Marszal and Heiselberg (2011) only monitored the energy consumed for heating, cooling, domestic hot water, ventilation in their research.

In conclusion, these reflections drawing on the examination of previous research indicate there is a great extent of inconsistency referring to the scope of costs and energy consumption of ZCBs. Such inconsistency is attributed to two factors: (1) that there is a lack of universal and formal guidelines and standards concerning how to define the scope of costs and energy; and (2) that the scopes of costs and energy consumption are defined with confusion and dimness. Therefore, the inconsistency highlighted here calls for new knowledge of a system framework referring to how to set the scopes of costs and energy. This paper proposes that an understanding of this will facilitate a better grasp of the principles for the life cycle cost and energy consumption analysis of ZCBs and consequently contribute to the further exploration of the cost-energy relationship of ZCBs.

FRAMEWORK OF THE COST AND ENERGY RELATIONSHIPS OF ZCBS

The system framework for the cost and energy relationship of ZCBs is developed in this research that controls the way in which costs and energy consumption are correlated with each other in a holistic manner. The system framework embraces two layers, i.e. internal and external layers. The internal layer illustrates the interior relationships between the cost, energy and lifespan of ZCBs through a three-dimensional conceptual model; the external layer describes outside context including stakeholder, climatic context and regulatory context, which in turn affect the definition of the scopes of costs and energy consumption. The development of this system framework is based on the reflections that identified through the literature review (Figure 2).

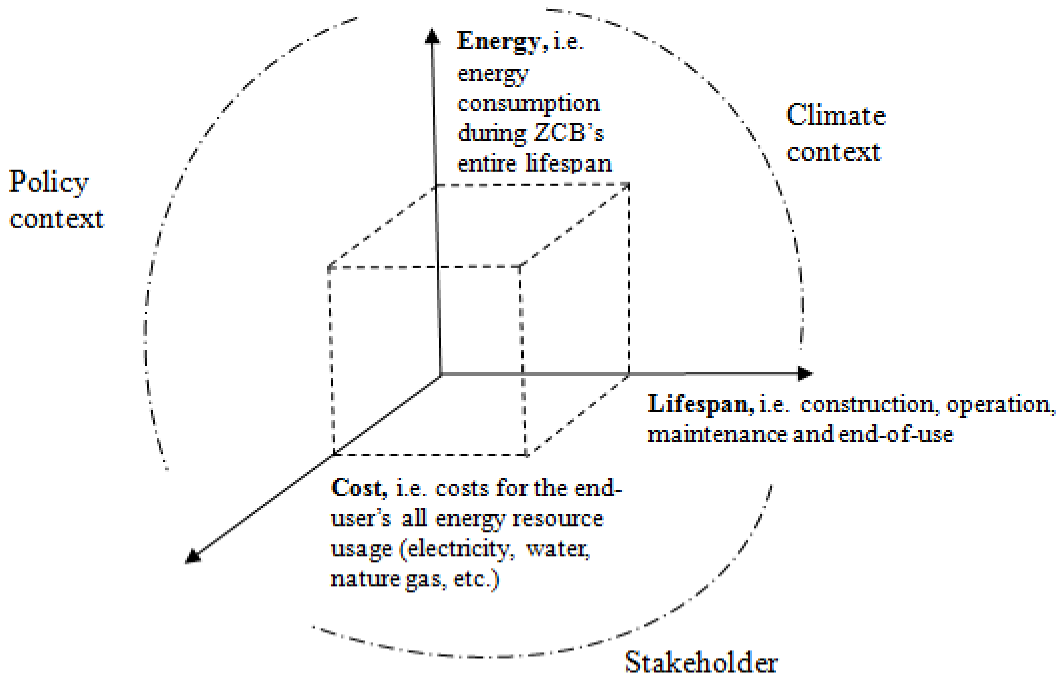

Figure 2: A framework of the cost and energy relationship of ZCBs from the life cycle perspective

Three-dimensional model

The conceptual three-dimensional model describes the cost and energy relationship of ZCBs through its lifespan (Figure 2). The scopes of these three dimensions are closely related with each other. How to define the scopes of these three dimensions are going to be discussed

- Lifespan dimension

The lifespan dimension denotes how to divide the lifecycle stages as well as set the lifespan of ZCBs. The construction and operation stages are prioritized over the maintenance and end-of-life stages for the life cycle costs in the existing research, while the operation stage is prioritized for the life cycle energy consumption. Such preference is primarily attributed to two factors: (1) that there is a lack of strict classification for the lifecycle stages of a building; and (2) the lifecycle phrases are continuously extending backward to the upstream manufactory industry and forward to the recycling business with the growing wider economic and environmental concerns. Drawing on the classification of the ISO 15686-5(BS 2012), this paper considers the full building lifecycle to cover construction, operation, maintenance and end-of-life stages. As for the extra consideration for the pre-construction phrase suggested in the life cycle assessment, the costs for procurement, transportation and other activities involved in the pre-construction phrase are all together included in the construction costs, and also, as for the energy consumption, the embodied energy have already covered all the energy consumed in the pre-use phase. Thus, it is redundant to specially divide a separate pre-construction stage within the lifespan of ZCBs. Meanwhile, the research lifespan of ZCBs should theoretically be the anticipated service life of the ZCB and any shorter lifespan that is applied cannot ensure sufficient time for the ZCB to maximize its economic efficiency. Yet, extra considerations should be paid to the uncertainties of assumptions on occupant behaviours and the discount rate if longer lifespan is applied.

- Cost dimension

The cost dimension denotes the cumulated costs of the ZCB along its lifespan. The difficulty associated with the costs calculation lies in forecasting the future operation, maintenance and end-of-use costs (Sesana and Salvala,2013). According to Fabrycky and Blanchard (1991), parametric estimation method should be preferred in predicting the future costs. This method is suggested to be of a lot help to forecast the incurring costs of the ZCB in the operation and maintenance stages. Meanwhile, it has been demonstrated by Korpi and Ala-Risku (2008) that the industry had a clear effect on the cost estimation method used and they further concluded that construction division used a lot of analogy with the estimation. The analogy method can be used solely or in combination with other real estate evaluation approaches, like hedonic pricing method (Morrissey &Horne, 2011), to predict the end-of-use costs of the ZCB, no matter whether the ZCB will be demolished or resold.

- Energy dimension

Major efforts have been made to reduce the energy use for building operation even at the price of increasing energy use in the production phase (Gustavsson *et al*, 2010). Scholars have been realized that the energy used in the construction and operation stages should be balanced simultaneously. Therefore, there is an increasing awareness for the necessity of taking the embodied energy into the energy balance of ZCBs account. Moreover, in many studies where the energy consumption arose in the end-of-life stages of buildings have been considered, like recycle and landfill (Junnila *et al*., 2006; Ochoa *et al*., 2002). However, despite this wide awareness of the energy consumption in construction and end-of-use stages, the difficulty regarding on quantifying the embodied energy and energy consumed in the final stage need to be conquered before achieving energy conservation throughout the whole lifecycle of ZCBs.

Moreover, there is an enormous deviation in terms of occupant behaviours, which are directly relevant to the overall energy use and building economy (Gill *et al*., 2011; Blight and Coley, 2013; Williamson, 2010).The UK definitions of ZCB transforms from the originally proposed *"genuine"* or *"complete"* zero carbon (which includes both regulated energy for space heating, cooling, ventilation, lighting and hot water; and unregulated energy for cooking, washing, and domestic entertainment appliances (DCLG, 2006)) to regulated energy only (HM Treasury, 2011). Besides that, Moore and Morrissey (2014) also recognized the behaviours of the occupants for energy consuming activities should fall outside the energy scope. Hence, the deviations concerning the occupant behaviours can be excluded by only meeting the regulated energy demand.

The relationships between the cost and energy consumption of ZCBs

Overall, although the dimensions are described separately, they are closely related with each other. The cost and energy consumption of ZCBs will be both determined and affected by some critical factors, i.e. human, materials and building itself. Specifically, as for the human factor, occupant behaviours will significantly impact the energy consumption of ZCBs and the associated incurring costs. As for the materials factor, the embodied energy will be embedded in the construction materials during the manufacture process and those materials will further consume energy through the construction activities, and also, the purchases of the materials will corresponding increase the construction costs. As for the building factor, the maintenance of ZCBs will cause extra energy consumption and the related costs. Therefore, there are some correlations between the cost and energy of ZCBs and these relationships can be revealed on the condition that the scopes of costs and energy consumption are defined distinctly.

External context

- Stakeholder

Life cycle costing is an economic methodology for selecting the most cost-effective design alternative over a particular time frame. However, different stakeholders have different short-term and long-term interests. The scopes of costs set for different stakeholders are varying from developers to building owners, and ZCBs for different purposes, i.e. residential and commercial buildings, will also have different cost scopes.

- Climatic context

Climatic conditions are another important external context that refers to the climatic zones in which the ZCB is located, such as tropical, sub-tropical, temperate and frigid zones. The climatic context is a significant consideration when simulating the energy consumption of ZCBs. Different countries or regions in different climatic zones have different energy consumption intensities. For example, countries in tropical or sub-tropical zones, like Singapore, may have more cooling energy consumption compared to countries located in mild climatic regions.

- Policy context

The regional or worldwide regulations, standards and policies concerning ZCBs practice closely impact the cost and energy relationship of ZCBs. The definitions and technical requirements for ZCB approach will be clearly illustrated in relevant policies, which give specific requirements for energy consumption or carbon emissions of ZCBs.

CONCLUSIONS

The purpose of this study was to develop a system framework of the cost and energy relationship of ZCBs from the life cycle perspective. Stemming from the critical review, it is concluded that there is a significant extent of inconsistency in defining the scopes of both costs and energy consumption of ZCBs. That is attributed to the confusion and dimness in the definition of both buildings' costs and energy consumption. Such inconsistency hinders the cost-energy relationship from being revealed. Therefore, the developed system framework contributes to demonstrate the correlation between the cost and energy of ZCBs and has useful implications for the building design decisions about the trade-offs between buildings’ economic efficiency and energy consumption.

REFERENCES

Aye L, Bamford N, Charters B and Robinson, J (2000) Environmentally sustainable development: a life-cycle costing approach for a commercial office building in Melbourne, Australia. *“Construction Management and Economics”*, **18**(8): 927-934.

Aktas, C B and Bilec, M M (2012) Impact of lifetime on US residential building LCA results. *"The International Journal of Life Cycle Assessment"*, **17**(3), 337-349.

Adalberth, K (2000) *"Energy use and environmental impact of new residential buildings"* ,Doctoral dissertation, Lund University.

Blight, T S and Coley, D A (2013) Sensitivity analysis of the effect of occupant behaviour on the energy consumption of passive house dwellings. *"Energy and Buildings"*, **66**, 183-192.

BS (2012) "*BS ISO 15686-5:2012.Building &construction assets—service life planning—Part 5:Life cycle costing*". British Standards.

BS (2012) "*EN 15643-4:2012.Sustainability of construction works. Assessment of buildings*." Framework for the assessment of economic performance.

Butler, D (2008) Architects of a low-energy future. *"Nature"*, **452**(3), 520-523.

Cuéllar-Franca, R M and Azapagic, A (2014). Life cycle cost analysis of the UK housing stock. *"The International Journal of Life Cycle Assessment"*, **19**(1),174-193.

Crawley D, Pless S and Torcellini P (2009) Getting to net zero. *"National Renewable Energy Laboratory"*,**51**(9),18–25.

Department for Communities and Local Government (DCLG) (2006) "*Building a greener future: towards zero carbon development: consultation*". London.

EU. Directive(2010) EU of the European Parliament and of the Council of 19May 2010 on the energy performance of buildings (recast). "*Official Journal of the European Union*".

Entrop, A G, Brouwers, H J H and Reinders, A H M E (2010) Evaluation of energy performance indicators and financial aspects of energy saving techniques in residential real estate. *"Energy and Buildings"*, **42**(5), 618-629.

Fabrycky, W J and Blanchard, B S (1991) "*Life cycle cost and economic analysis*". Prentice-Hall, Englewood Cliffs, NJ.

Feist, W (1997) "*Life-cycle energy analysis: comparison of low-energy house, passive house, self-sufficient house*". Passive House Institute.

Gill, Z M, Tierney, M J, Pegg, I M and Allan, N (2011). Measured energy and water performance of an aspiring low energy/carbon affordable housing site in the UK. *"Energy and Buildings"*, **43**(1), 117-125.

Gustavsson, L, Joelsson, A and Sathre, R (2010) Life cycle primary energy use and carbon emission of an eight-storey wood-framed apartment building. *"Energy and Buildings"*, **42**(2), 230-242.

Hootman T(2012) Net zero energy design: a guide for commercial architecture. *"John Wiley and Sons"*.

HM Treasury (2011) "*The plan for growth*". London:HM Treasury.

Horne, R and Hayles, C (2008) Towards global benchmarking for sustainable homes: an international comparison of the energy performance of housing. *"Journal of Housing and the Built Environment"*, **23**(2), 119-130.

HM Treasury(2011) "*The Plan for Growth*". London: HM Treasury.

Jakob M (2006) Marginal costs and co-benefits of energy efficiency investments. The case of the Swiss residential sector. *"Energy Policy"*, **34**(2), 172-187.

Junnila, S , Horvath, A and Guggemos, A A (2006) Life-cycle assessment of office buildings in Europe and the United States. "*Journal of Infrastructure Systems*", **12**(1), 10-17.

Kneifel, J (2010). Life-cycle carbon and cost analysis of energy efficiency measures in new commercial buildings. *"Energy and Buildings"*, **42**(3), 333-340.

Korpi, E and Ala-Risku, T (2008) Life cycle costing: a review of published case studies. *"Managerial Auditing Journal"*, **23**(3), 240-261.

Li, D H, Yang, L and Lam, J C (2013) Zero energy buildings and sustainable development implications–a review. *"Energy"*, **54**, 1-10.

Marszal, A J and Heiselberg, P (2011). Life cycle cost analysis of a multi-storey residential net zero energy building in Denmark. *"Energy"*, **36**(9), 5600-5609.

Moore, T and Morrissey, J (2014) Lifecycle costing sensitivities for zero energy housing in Melbourne, Australia. *"Energy and Buildings"*, **79**, 1-11.

Moore, T. (2012) *"Facilitating a transition to zero emission new housing in Australia: Costs, benefits and direction for policy"*, Doctoral dissertation, RMIT University.

Moore T (2014) Modelling the through-life costs and benefits of detached zero (net) energy housing in Melbourne, Australia. *"Energy and Buildings"*, **70**, 463-471.

Mequignon, M, Adolphe, L, Thellier, F and Haddou, H A (2013) Impact of the lifespan of building external walls on greenhouse gas index. *"Building and Environment"*, **59**, 654-661.

Morrissey, J and Horne, R E (2011) Life cycle cost implications of energy efficiency measures in new residential buildings. *"Energy and Buildings"*, **43**(4), 915-924.

Ochoa, L, Hendrickson, C and Matthews, H S (2002) Economic input-output life-cycle assessment of US residential buildings. "*Journal of Infrastructure Systems*", **8**(4), 132-138.

Pan, W (2014) System boundaries of zero carbon buildings. *"Renewable and Sustainable Energy Reviews"*, **37**, 424-434.

Pan, W and Ning, Y (2015) A socio-technical framework of zero-carbon building policies. *"Building Research and Information"*, **43**(1), 94-110.

Ryghaug M and Sørensen K H (2009) How energy efficiency fails in the building industry. *"Energy Policy"*, **37**(3), 984-991.

Sesana, M M and Salvalai, G (2013) Overview on life cycle methodologies and economic feasibility for nZEBs. *"Building and Environment"*, **67**, 211-216.

Scheuer, C, Keoleian, G A and Reppe, P (2003) Life cycle energy and environmental performance of a new university building: modeling challenges and design implications. *"Energy and buildings"*, **35**(10), 1049-1064.

Treasury HM (2008) "*Budget 2008 stability and opportunity: building a strong, sustainable future*". London: The Stationery Office.

Williamson, T, Soebarto, V and Radford, A (2010) Comfort and energy use in five Australian award-winning houses: regulated, measured and perceived. *"Building Research and Information"*, **38**(5), 509-529.

Winther, B N and Hestnes, A G (1999) Solar versus green: the analysis of a Norwegian row house. *"Solar energy"*, **66**(6), 387-393.

Zhu, L, Hurt, R, Correa, D and Boehm, R (2009). Comprehensive energy and economic analyses on a zero energy house versus a conventional house. *"Energy"*, **34**(9), 1043-1053.